AN EXPERIMENTAL STUDY OF THE EFFECT OF LIQUID PROPERTIES ON PACKED TOWER OPERATION

BY

WILLIAM JAMES WALSH

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William James Walsh

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NOMENCLATURE

a Total surface area of packing, sq. ft./cu. ft. of packed tower volume.

A Area of cross section of empty tower, sq. ft.

D_p Diameter of a packing unit, ft.

F, F_d Fractional dry voids in packing, cu. ft./cu. ft. of packed tower volume.

g_c conversion factor, lbs.(f), sec^2/ lbs.(m), ft.

G mass velocity of gas on basis of open cross section of tower, lbs./hr., ft^2.

H Holdup, lbs./cu. ft. of packed tower volume.

L Mass velocity of liquid on basis of open cross section of tower, lbs./hr., ft^2.

N Height of packed bed, ft.

P Gas pressure drop through packed bed, inches of water.

u, V Linear velocity of gas on basis of open cross section of tower, ft./sec.

ρ Fluid density, lbs./cu. ft.

μ Fluid viscosity, centipoises.

CHAPTER I

INTRODUCTION

Many chemical processes involve operations characterized by the transfer of material by diffusion from one phase to another. Absorption, rectification, humidification, stripping and extraction are typical of these operations.

Diffusional processes are commonly carried out in packed towers the primary purpose of which is to provide a large surface of contact for the liquid and gas. Essentially these packed towers consist of vertical, cylindrical columns filled with selected packing materials. Almost all towers use counter-current flow in which the liquid trickles down over the packing while the gas rises through the spaces between the packing units. In the past a wide variety of irregularly shaped materials have been used for tower packing, but the tendency in recent years has been to use fabricated packings made of chemical stoneware, porcelain, carbon or metal.

Although packed towers are as old as the chemical industry, the apparatus in commercial use has never become standardized. Thus each installation requires complete specifications from the design engineer.

I. THE PROBLEM

Statement of the problem. It was the purpose of this study: (1) to build pilot plant equipment suitable for measuring the gas pressure drop and the liquid holdup, in absorption type packing; (2) to obtain consistent data on packed tower operation using several types of packing materials and liquids of varying physical properties.

Importance of the study. The necessary theoretical background for the design of a packed tower, even in its physical aspects, is relatively complex and not well understood. Thus the primary guide of the design engineer is performance data. However available data on packed tower performance is meager and scattered, the results often inconsistent, and the correlations inconclusive.

The height and diameter of the tower and the gas pressure drop are major design considerations. The amount of absorption or stripping usually determined the height. The diameter and pressure drop are principally determined from consideration of the gas velocity.

The gas velocity must satisfy limitations imposed by the flooding point and by the cost of tower construction and operation. It must be rather far removed from the flooding point for stable operation. But it must not be so small as to require an excessively large diameter for

handling the required throughput, and thus a high installation cost; nor can it be so great as to require large operating expenses. With regard to this latter point Sherwood[17] states:

> Apart from general maintenance, the power required to force the gas up through the packing frequently represents the principle operating cost of a packed tower. The power cost is proportional to the product of the gas rate and the pressure drop through the tower thus data on pressure drops at various gas rates are of first importance for design purposes.

This work extends the available literature by presenting performance data on the physical aspects of a tower packed with various packing materials and operated with liquids of various physical properties. The variation of pressure drop values with gas velocity is fully covered, as are the flooding points for a wide range of liquid rates. In addition the basic understanding of packed tower operation is advanced by the presentation of information on other variables, such as holdup, which theoretical considerations indicate are influencing factors on pressure drop and flooding points in packed towers.

II. DEFINITIONS OF TERMS USED

Due to the practical nature of this field and its lack of theoretical foundation, especially in its physical aspects, many terms have arisen which have been variously interperted. For this paper the following definitions are applicable.

<u>Velocity</u>. Unless otherwise specified this term is

the superficial velocity or "velocity of approach" of the gas or liquid. It may be obtained by dividing the volumetric rate by the cross section of the empty tower.

Flooding point. The gas velocity at which a layer of liquid just begins to form on top of the packing material.

Void space. The volume available for gas and liquid flow during tower operation. It is the volume of the empty tower less the volume of the dry packing.

Drained void space. This is the void space less the liquid retained in the packing, after tower operation, at zero gas velocity.

Holdup. The liquid which is present at all times in the tower during stable operation at a given gas and liquid rate, less that retained by the packing at zero gas velocity.

Pressure drop. Unless otherwise specified this term applies to the actual loss in pressure of the gas stream while flowing through the packed bed.

III. ORGANIZATION OF THE REMAINDER OF THE THESIS

The remainder of this thesis will present the results of the work carried out for the fulfillment of this study. It will include in Chapter II a review of previous related work; in Chapter III the requirements and design of the equipment used; in Chapter IV details of the experimental procedure.

The results will be presented and discussed in Chapter V and Chapter VI will contain a summary of the work and the conclusions to be drawn therefrom.

CHAPTER II

HISTORY OF THE PROBLEM

The consideration given in the literature to pressure drop, flooding point, holdup and other physical aspects of packed towers are to a great extent useful only for the specific problem investigated and allow little more than limited interpolation. Therefore this review of the literature will consider those works which are primarily concerned with the interpertation and extention of knowledge of the physical behaviour of packed towers. It will review these works under the headings of pressure drop, holdup, and flooding point.

I. PRESSURE DROP

The variables upon which pressure drop depends are many and complex. A complete analysis must include the following:

1. For each fluid

    a. density
    b. viscosity
    c. surface tension
    d. rate of flow

2. For the bed

    a. diameter
    b. height
    c. void space
    d. holdup

3. For the packing

    a. shape
    b. orientation
    c. surface roughness

Although the literature contains numerous references to pressure drop studies, in almost all cases many of the variables are ignored. Such an important variable as void space is rarely reported. These investigations are therefore limited in use to equipment of a similiar nature, similiarly packed. A rather complete listing of such works is found in Zenz[21] as well as in Perry[15], pages 687-684.

The behaviour of all packed towers is essentially the same. At low gas and liquid rates the pressure drop is approximately proportional to the square of the gas velocity. However if the gas rate is increased at constant liquid rate a point is reached above which the pressure drop becomes proportional to a power greater than the square of the gas velocity. This has been termed the loading region. As the gas rate is increased still further the flooding region is encountered. This region is characterized by exceedingly large pressure drop variations with small changes in the gas rate.

Although there is little doubt that the above described behaviour is the result of a continuous variation of flow conditions within the tower, many investigators have found

it convenient to plot the logarithm of the pressure drop against the logarithm of the gas rate at constant liquid rate and draw straight lines through the experimental points. This results in three connected straight lines and two break points. The gas velocity at which the lower break point is found is termed the loading velocity, the upper the flooding velocity.

Zeisberg[20] experimentally showed that the general law of fluid flow holds for packed towers and thus reasoned that the frictional resistance between the packing and the gas must be proportional to the square of the gas velocity. He expressed this resistance as the pressure necessary to produce the given flow and derived the equation:

$$\Delta P = \frac{fNv^2}{A^2} .$$

f is designated as the frictional coefficient of 1 square foot of packing one foot high. It differs with each type of packing, method of packing and liquid rate. This coefficient was evaluated for a variety of packings both dumped and stacked, with no liquid flow and packing dry, with no liquid flow and packing wet with water but drained, and with water circulating at the rate of 11 pounds per minute per foot squared. However the range of gas velocities is not given.

Chilton and Colburn[5] suggested that the gas pressure drop is primarily due to expansion and contraction losses suffered by the gas flowing through the irregular orifices formed by the packing units, and estimated that only about ten percent of the drop is due to skin friction. Since expansion and contraction losses, as well as frictional losses, are approximately proportional to the square of the gas rate they based a correlation of the data available in 1931 on the Fanning equation for friction in pipes. For single phase fluid flow through uniform granular solid particles it took the form

$$\frac{\Delta P}{N} = \frac{2f' G^2}{g_c \, D_p \rho}$$

where f' is a function of a modified Reynolds number, $D_p G/\mu$. Empirical factors are given to use in accounting for hollow shapes such as Raschig rings and Lessing rings, and for "wall effect". This latter is the variation in void space with tower diameter for the same packing material due to the particles adjacent to the wall packing more loosely than those in the interior of the tower.

White[19] extended this correlation to two phase flow by further empirical factors. However the latter are available only for gas velocities of 0.5, 1.0, and 2.0 feet per second and apply only when water is the counter-current liquid. This latter fact plus the obvious omission

of the void space, although this is indirectly compensated for by the "wall effect" factor, leaves something to be desired in this correlation.

Zenz[21] has proposed an equation for calculating the pressure drop in counter-current, gas-liquid packed towers. This equation is based on an analogy to adiabatic flow through valves and orifices. His idea is that since the tower holdup is approximately independent of the gas rate the gas flow, at constant liquid rate, will be similiar in character to that through any other constricted portion of fixed cross section. An extensive trial and error method was used to located pressure drop curves based on the available data. They apply fairly well at low liquid rates but deviate above a certain "critical" liquid rate. To use the equation a knowledge of this "critical" liquid rate is required, as well as both the gas and liquid rates at flooding or pressure drop data at some point below flooding. This would seem to make it no different than curves arbitrarily fitted to the data.

Brownell and Katz 2,3,4, have, as was done with the Chilton and Colburn correlation, enlarged their own general correlation for single phase flow through porous media to cover the flow of two fluid phases. They attempted to include in this correlation all the factors upon which pressure drop depends. The equation takes the form:

$$\frac{\Delta P}{N} = \frac{f'' \; V^2 \rho}{2 \, g_c \, D_p \, F_f}$$

The factor f'' is obtained from the curves of Moody[13] for flow through empty pipes when the Reynolds number is calculated as

$$Re = \frac{D_p \; G}{\mu \; F_{Re}}$$

The factors F_f and F_{Re} are presented from experimentally derived curves and are dependent on particle shape and bed porosity. For two phase flow the particle shape is given as a function of the holdup for each packing size and type. However the determination of these factors from the curves presented is so difficult in the two phase flow region that differences of 100% in the calculated pressure drop are readily obtained from the same basic data.

Leva[10] derived an equation for calculating the gas pressure drop through dry beds from an analogy to flow in empty pipes. The equation has the form

$$\Delta P = \frac{2.12 \, f''' \; G^2 \lambda \, N \, (1-\delta)}{D_p \; g_c \rho \, \delta^3}$$

λ is a factor to account for the particle shape, δ is the void space in the bed, f''' is a modified friction factor inversely proportional to the Reynolds number. Leva reports in reference 11 that this equation may be used for estimating pressure drop through irrigated systems if the dry void space is corrected to account for the holdup. Only fair results

can be expected and these at very low liquid rates, for the wetting fluid on the surface of the particles will effectively change their shape and thus λ.

Leva also reports, in reference 11, pressure drop data collected from the literature and supplemented by data from the laboratories of the U. S. Stoneware Company. Using the formula $\Delta P = \alpha \cdot 10^{\beta L} \cdot \frac{G^2}{\rho}$ the values of the constants α and β are given for various sizes of rings and saddles. However the data pertains only to the system gas-water and applies only if the voidage values are substantially the same as those reported.

II. HOLDUP

Holdup, the quantity of liquid present in the tower during stable operation, has received the attention of some investigators who endeavored to relate this quantity with other variables for the solution of mass transfer problems in packed towers. Notable among these are the works of Payne and Dodge[14], Simmons and Osborne[16], and Cooper, Christl and Perry[6]. However the investigations of pressure drop in packed towers has lead to a more complete study of this important variable.

Elgin and Weiss[7] using a water-air system in a 2.89 inch column reported that gas velocity has no appreciable

effect on holdup, over that existing at zero gas flow, for a constant liquid rate until a "critical gas velocity" not far removed from the flooding velocity was reached beyond which point the holdup rises rapidly. Their work covered four packing materials one-quarter and one-half inch Berl saddles, 0.625 inch Raschig rings and one-half inch clay spheres.

Jesser and Elgin[9] studied the effect of liquids of various physical properties on holdup with no gas flowing. They determined that "holdup is an exponential function of liquor velocity and this exponent is essentially the same for any one type of packing, irrespective of size." They summarized the available data on water holdup at various rates at zero gas velocity of previous investigators. They also presented an equation for estimating holdup in systems working with liquids other than water.

Jesser and Elgin[9] recognized that holdup in packed towers is not a single quantity, but rather the sum of several "operating" and "static" holdups arising from different causes. Brownell and Katz[3] present a mechanism to explain the causes of these components and set up equations by means of which they may be calculated.

III. FLOODING POINT

As has been pointed out the design diameter of a packed tower operated counter-currently is determined by the quantity of gas to be treated. The determining factors are the pressure drop and the flooding point of the gas. It was suggested that a large pressure drop has a major effect on the operating cost of the tower, while a low pressure drop frequently requires a large diameter and consequently an increased first cost of equipment and installation. But, in addition to these important considerations it must at all times be remembered that if either the gas or liquid velocity is increased the pressure drop through the packing increases and eventually a point is reached when the holdup increases, the pressure drop rises sharply and the tower enters the flooding region. This region is characterized by gas bubbling through the liquid, violent entrainment and pressure drop fluctuating greatly with small changes in gas velocity. The unsteady characteristics of the tower in this region necessitates operating velocities well below the flooding region.

Although flooding is actually a region or range of velocities this fact has not always been appreciated by previous investigators. But even when it is so recognized it is desirable to define a point in this region for

reasons of comparison and reproduction. This has been done in all cases, but unfortunately the definitions do not refer to the same point. Thus in one sentence in Perry[15], page 683, the following three definitions of the flooding point are given. "The flooding point has been defined as the gas velocity at which a liquid layer builds up on top of the packing, as the second break point on a log-log plot of pressure drop vs. gas velocity, and also as the point at which the measured liquid holdup increases abruptly." Due to the fact that the pressure drop changes markedly with small changes in gas velocity and this in turn changes the other characteristics such as entrainment all flooding point definitions result in essentially the same velocity, but for the same reasons the pressure drops reported at flooding differ widely.

Several investigators have presented correlations to predict the flooding velocity. However the one general correlation that is most valuable today is that of Sherwood, Shipley and Halloway[18]. It can be applied to a variety of packings and is based on a great range of data. This correlation is presented as a single curve. The ordinate is the logarithm of $\frac{V^2}{g_c}\frac{a}{F^3}\frac{\rho_G}{\rho_L}\mu_L^{0.2}$. The abcessa is the logarithm of $\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$. Lobo et al[12] have shown that this correlation gives an average deviation of 11.5% from a large

volume of experimental data when the measured values of a/F_d^3 are used rather than the values reported by the packing manufacturers.

CHAPTER III

EQUIPMENT AND MATERIALS

For precise results the following requirements for the experimental apparatus were established:

1. The liquid system must be capable of the following:

    a. provide all flow rates from 0 to 6 gallons of water per minute.

    b. handle and recirculate liquids with viscosities up to 30 centipoises.

    c. maintain the liquid rate within close limits.

    d. accurately indicate the liquid rate.

    e. hold the liquid temperature within one degree Fahrenheit.

    f. accurately indicate the liquid temperature.

    g. allow instantaneous cut off of liquid flow to the tower and precise collection of the tower holdup.

    h. maintain a liquid seal of constant level in the bottom of the tower.

    i. provide suitable distribution of liquid on top of the packing.

2. The gas system must be capable of the following:

    a. provide air flow at all rates from 0 to 10 cubic feet per minute.

    b. maintain a constant air flow rate.

    c. accurately indicate the air rate.

d. protect the air system from any liquid which might gain entrance thereto.

e. provide suitable distribution of the air in the bottom of the tower.

3. The tower must have the following characteristics:

   a. be transparent.

   b. be easily dumped of packing and easily repacked.

   c. have a diameter at least eight times greater than the particle diameter of the packings to be used.

   d. provide for at least three feet of packed height.

   e. have a packing support which causes negligible gas pressure drop compared to that of the packing.

4. The gas pressure drop system must be capable of the following:

   a. accurately record all pressure drops across the tower from one tenth of an inch of water to twenty inches of water.

   b. be unaffected by any water which might enter the system.

In addition to the above it was considered most desirable to have a set-up which could be easily and completely controlled by a single operator.

I. FINAL APPARATUS

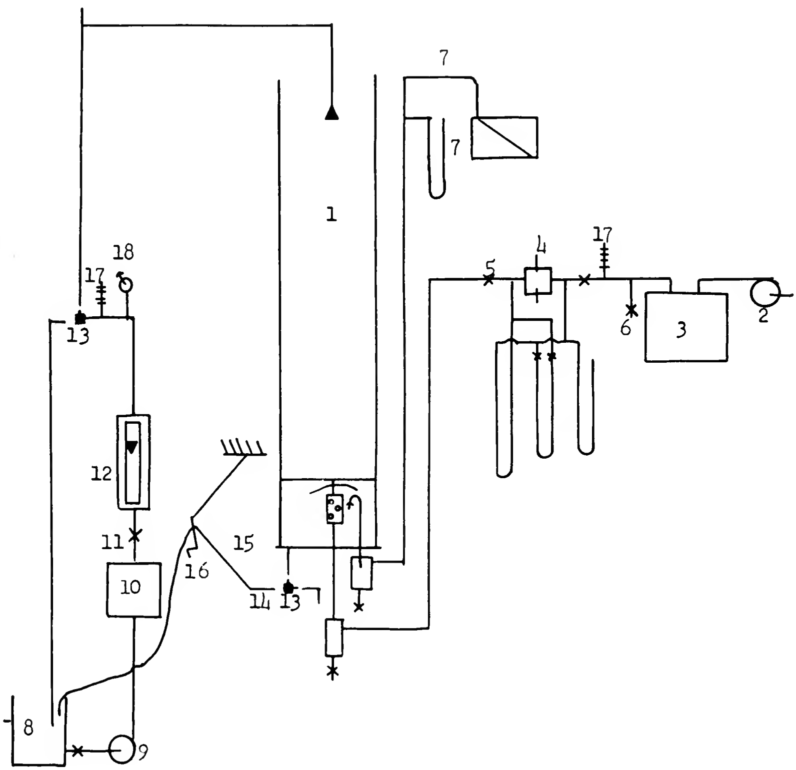
The above requirements were not evident, nor were the problems which they presented solved, all at once. However after much work the final set-up was designed and built

as shown in Figures 1 and 2, pages 20 and 21, and as described below.

<u>The liquid system</u>. A 20 gallon per minute centrifugal pump run by a one horsepower motor took suction from a 60 gallon tank in which the level was maintained constant and delivered the liquid through one inch standard pipe to the top of the tower. Rate control was obtained by a gate valve located just below a calibrated rotameter. Two liquid distributors were used individually to achieve good distribution of liquid on top of the packing at low and high flow rates. Both distributors were made with dished aluminum heads containing 19 orifices, 12 of which were located on a 7/8 inch circle, 6 on a 3/8 inch circle and one in the center. The orifices in the fine spray head were 0.025 inches in diameter, while the coarse spray had 0.2 inch diameter orifices.

The rotameter was calibrated at each setting used in the course of the experiments. This was done by collecting and weighing the liquid to be used, during a known time interval. Check runs were made in each case, the maximum deviation being 1%.

Because a centrifugal pump was chosen difficulty was encountered due to the heating up of the more viscous liquids as well as water at low flow rates as they passed



1. Glass Tower
2. Air Blower
3. Surge Tank
4. Air Orifice
5. Air Control Valves
6. Bleed Off Valve
7. ΔP Manometers
8. Constant Level Tank
9. Liquid Pump
10. Heat Exchanger
11. Liquid Control Valve
12. Liquid Rotameters
13. 3-way Plug Cocks
14. Swivel Joint
15. External Standpipe
16. Crank for Standpipe
17. Thermometers
18. Pressure

FIGURE 1

SKETCH OF EXPERIMENTAL APPARATUS

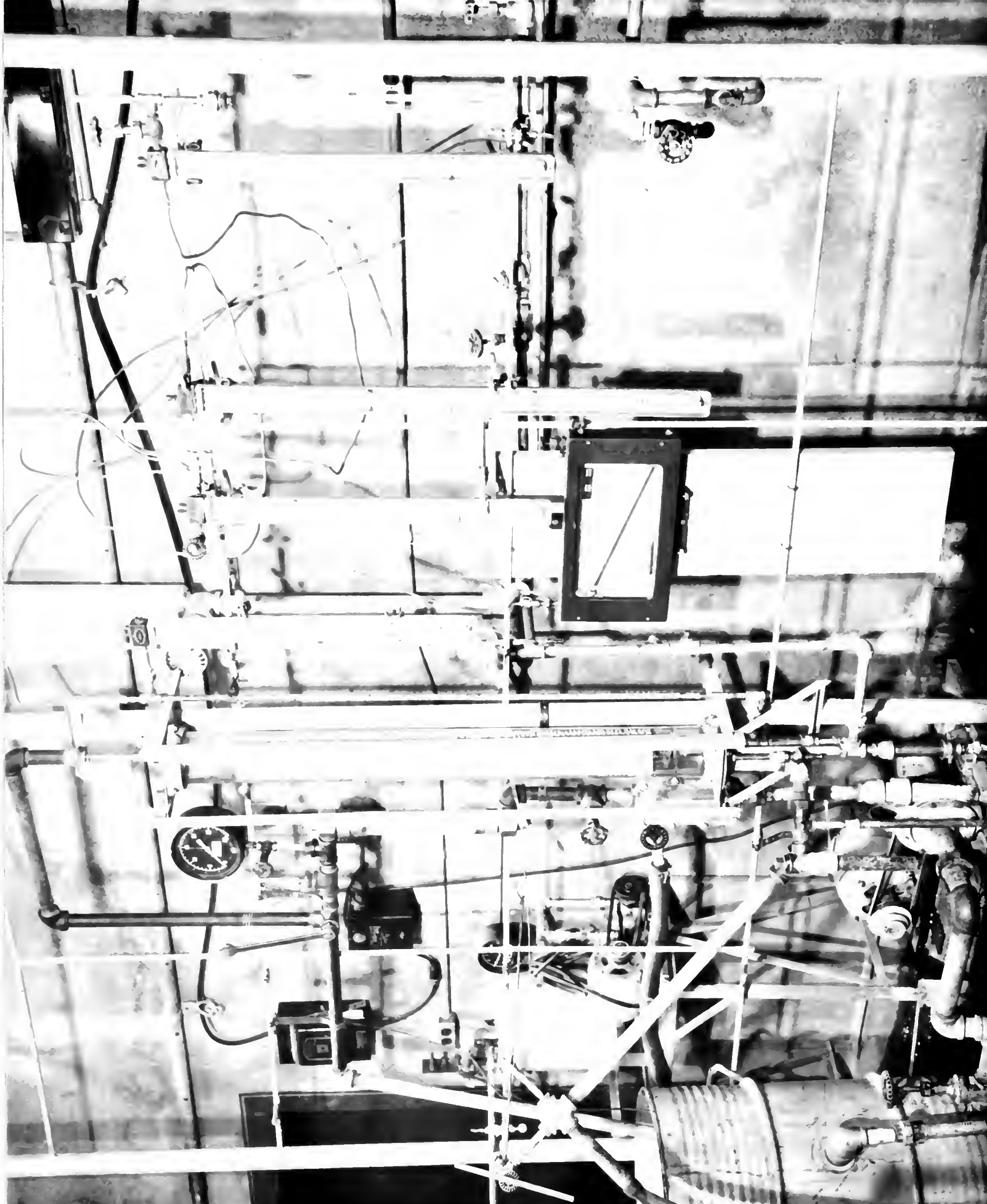


FIGURE 2

VIEW OF EXPERIMENTAL APPARATUS

through the pump. This caused an unacceptable variation in viscosity. To overcome this difficulty the liquid was sent through a heat exchanger which used city water at about 46° Fahrenheit as the cooling medium. This heat exchanger was placed in the line before the rotameter. Temperature control within 1° Fahrenheit was obtained at all flow rates, for all liquids used, by hand setting of the cooling water control valve. Temperature was indicated by a bare bulb thermometer inserted directly in the line.

A liquid seal was maintained on the bottom of the column to allow the gas to flow directly into the tower without the possibility of loss by way of the liquid drain pipe. This seal was maintained and its level controlled by a stand pipe connected to the liquid drain pipe with a swivel joint. The level in the tower could be readily raised or lowered by changing the angle at which the external standpipe was set. The liquid outlet from the tower was sent to the sewer in the case of water, but was returned to the suction tank when other liquids were used.

Measurement of the liquid holdup in the tower was accomplished by means of an instantaneously acting cut-off system which simultaneously cut off the liquid entering the tower and re-directed the liquid leaving the tower to a weigh tank. This cut-off system consisted of 2 three-way

plug cocks so located in the liquid inlet and exit lines that the required action could be brought about by one operator giving each plug a one quarter turn at the same time.

The gas system. Air was supplied to a surge tank by a rotary vane blower at a gage pressure of 12 pounds per square inch. From the tank the desired amount of air was led through an orifice meter and into the bottom of the tower. The blower output was constant and the desired flow rate was achieved by adjusting the bleedoff from the surge tank. A constant upstream pressure of 8 inches of mercury was maintained at all times on the orifice meter. This was achieved by the two valve arrangement shown in Figure 1. Air temperature was measured by a bare bulb thermometer inserted directly into the line.

The orifice pressure drop was measured by a 36 inch U-tube manometer filled with Merriam #3 Indicating Liquid, and by a 24 inch U-tube manometer filled with water and connected in parallel for reading low pressure differentials. To cover the entire range of gas rates three orifice plates were required. These were inserted and removed as necessary. All orifice pressure drop-air rate calibration charts were drawn using measurements made with a diaphram gas meter of known capacity and a stop watch over a suitable period to give an accuracy of 2%.

A series of drilled holes in the 1/2 inch gas inlet pipe served as the gas inlet ports. A two and one half inch diameter umbrella was installed above the gas ports to prevent liquid from flowing into the gas pipe. However at low air rates some liquid did get into the air pipe and so a trap with drain cock was installed just below the inlet pipe, to collect it.

Tower. The tower was pyrex glass cylinder 4 inches in diameter by 5 feet high with conical flanged ends. The top of the tower was left open to the atmosphere, the bottom closed by a blank flange bolted so as to seal the bottom of the tower. This bottom end plate was pierced by the air inlet pipe, the liquid drain pipe and the pressure drop manometer line. It was easily removable so that the packing could be removed and replaced.

The packing support was a wire grid of the design described by Bain and Hougen[1]. This grid was such that the available void space in the support was much greater than that in the packing. The wire grid was supported by the gas inlet pipe.

The gas pressure drop system. Pressure drop of the gas flowing through the column was measured by a 24 inch U-tube manometer filled with water, supplemented by a Meriam draft gage for pressure drop readings up to 4 inches

of water. This latter gage could read directly to 0.01 inches of water. Since the gas exhausted to the atmosphere it was only necessary to measure the difference in pressure between the bottom of the tower and the atmosphere. Thus one leg of the manometers was connected to the bottom of the tower, the other left open to the atmosphere.

A one eighth inch pressure tap extended through the bottom plate then was bent into a U shape under the protecting umbrella described above so that the tap faced downward. To avoid drops of liquid forming on the end of the tap, as well as to prevent venturi action of the gas, the end was split into 4 sections which were spread out and filed to points.

To prevent trouble from any liquid which might enter the pressure drop system a trap was attached to the line just outside the bottom flange. The trap was so constructed that no liquid could enter the manometer leads.

When equipped as described above the apparatus proved ideally suited for the purposes of this work. Once the liquid or gas rate was set it remained constant for long periods without re-adjustment. The level of the liquid seal in the tower bottom was easily set at the desired level and held there with no manipulation. This allowed the operator complete freedom to observe the flow

characteristics within the tower and to concentrate on the pressure drop variations to insure when stability was achieved. Likewise a single operator could easily manipulate the valves for holdup determinations. Thus all the basic requirements for the equipment enumerated above were fulfilled.

II. MATERIALS

The choice of the materials upon which the experimental work was to be carried out was dictated by three relatively incompatable considerations. It was desired first that the experimental materials be similiar in physical properties to those used in industrial operations, second that they be readily and cheaply obtained and third that they have physical properties which could be easily and directly determined with accuracy. The packing types, liquids, and gas actually chosen and the reasons therefore are presented in this section.

Packings. Two packing types were chosen, namely Raschig rings and spheres. This type of work almost demands Raschig rings. Leva[11], page 17, states that "probably the most common fabricated tower packing is the Raschig ring. Over the years it has found widespread use in installations of all sorts." The choice of spheres as the

second packing type was dictated by the symmetry of the particles rather than by more practical considerations. Certainly Berl saddles and spiral rings are more widely used, but due to their complicated dimensions and shape they are very difficult to describe mathematically.

Both of the chosen packing materials were made of chemical stoneware, which is common industrially. Also, both had a nominal particle diameter of three eighths of an inch. Thus the tower diameter was 10.7 times larger than the particle diameter and well within the limit of 6.0 specified by Lobo, et al[12] for neglecting the variation of $a/F_D{}^3$ with the ratio of tower diameter to packing size.

<u>Liquids</u>. Water has been an almost universal choice of investigators for work in this field. To check and extend this past work it was used in this work also. But the almost complete lack of data for other liquids demanded that they be considered. Particularly important is the need for data showing the effect of viscosity on pressure drop and thus that property was chosen as a major variable. The required variations in viscosity was achieved by diluting glycerine with distilled water. This was a particularly happy choice for the physical properties of the various dilutions were readily determined, and in addition glycerol solutions

are completely miscible with water and thus the tower packing was easily flushed before each series of runs at different viscosities.

Gas. Although information on gases of various physical properties is of course desirable it must nevertheless be considered that it is the gas mass velocity which has the major effect on pressure drop and flooding, while its density is of secondary importance and its viscosity of small effect in the turbulent range where most industrial towers are operated. Also the use of large quantities of commercial gases is expensive and unhandy in academic laboratories where it is not readily available and where facilities for its pumping and storage are not usually available. For these reasons air was the only gas used in the experiments reported in this work.

CHAPTER IV

PROCEDURE

The procedure used for the measurement of pressure drop and holdup was standardized in order to insure quantative and reproducible results. Preliminary experiments demonstrated the slowness with which the tower stabilized. For example it was found that for a given setting of the gas and liquid rates the pressure drop and holdup would rise rapidly to near their equilibrium values, but that an appreciable length of time was required to achieve true stability. Periods of as long as 5 minutes would see very small changes in the pressure drop, changes almost within the limits of experimental error. However waiting 15 to 20 minutes would produce significant changes. After stability was once achieved the readings remained constant.

When the experimental procedure had evolved and become standardized as a result of the preliminary runs it was found that not only could the author make check runs with good reproducibility but also separate groups of senior chemical engineering students, who operated the tower in the Fall of 1951 prior to the gathering of the experimental data presented in this report, could obtain pressure drop curves whose differences were well within experimental error.

Each run was independent of all others and resulted from a given setting of flow conditions. However the details of procedure were the same for all runs. These details are described under the following headings: packing the tower, setting the liquid and gas rates, taking readings, measuring the holdup, and measuring the properties of the fluids.

I. PACKING THE TOWER

For each type of packing material the average dimentions and weight of a single unit was obtained from the measurements of 100 individual units. Then the tower was "dry packed". With the packing support in place the packing was slowly dumped into the tower from the top so that random distribution of particles was obtained. No disturbance of the distribution, such as leveling off or filling some of the larger void spaces apparent at the walls, was permitted. The tower was filled in all cases to a height of 36 inches. The weight of packing required to give this height was measured, and the number of packing units in the tower was obtained therefrom. Prior to experimental runs, the tower was operated at a high liquid and gas rate to stabilize the packing.

Before each series of runs with a liquid of constant physical properties, the tower was slowly filled to the top of the packing with the liquid in question, being sure all air was displaced. Then the tower was drained to the bottom of the packing, the liquid being collected and weighed. Since the density of the collected liquid was known, the drained void space could be easily calculated.

II. SETTING THE LIQUID AND GAS RATES

For each run the liquid rate was set at the desired value, being careful not to exceed this value temporarily during the setting. It was found that if this latter event happened, the excess holdup occasioned thereby seriously retarded the attainment of stability. When necessary, cooling water for the heat exchanger was turned on and adjusted to give the desired liquid temperature. Next the liquid level in the bottom of the tower was set at the mark required for holdup determinations.

Once the liquid rate was set, gas was allowed to enter the tower and the rate built up to the desired setting by manipulation the two valves described in the previous chapter. Once again the gas rate was not allowed to exceed the pre-determined setting for the same reasons as given above for the liquid rate.

The equipment was such as to allow the liquid and gas rates to remain constant once set.

III. TAKING THE READINGS

At least 20 minutes were allowed to pass before readings were taken, although all indicating equipment was continually checked to insure that constancy of rate, temperature, etc. was being maintained. In particular the gas pressure drop gages were constantly watched for as the tower neared equilibrium the pressure drop rose very slowly. This close attention was particularly necessary in and near the flooding region. Although small changes in the gas rate cause large changes in the pressure drop in the flooding zone, these large changes were not always immediately evident. Sometimes as long as 60 minutes were required to achieve stability in this region, and this required patient attention to determine the defined flooding point. When satisfied in all respects that the tower was in stable operation all readings, except holdup, were recorded.

When all readings, including holdup, were recorded the next run was commenced by setting the same liquid rate but a different gas rate. The operating procedure was then repeated. In this way a series of gas rates all at a constant water rate was obtained extending from a low gas rate to the flooding point.

IV. MEASURING THE HOLDUP

For each run, after the readings described above were recorded, and after ascertaining that the liquid seal was at the correct level, the three-way plug cocks in the liquid inlet and drain lines were turned simultaneously so that the liquid flow to the tower was instanteously cut off and at the same time the drainage was diverted to the weigh tank. Immediately after this the gas flow to the tower was secured. In this way the amount of liquid in the weigh tank less the predetermine amount of liquid from the spray head and present in the drain line was the actual holdup in the tower.

Holdup determinations were also made at zero gas flow for all liquid rates in the same manner.

V. MEASURING THE FLUID PROPERTIES

The physical properties of the liquids which are important for this work are density, viscosity and surface tension. In the case of water the values of these properties, at the experimental temperature, were taken from tables in the Handbook of Chemistry and Physics[8]. Specifically the table used for density is on page 1695, viscosity on page 1729 and surface tension on page 1721. For glycerol the density was determined by a Westphal balance. With this

value of density the percentage of glycerol was obtained from Table 136 on page 191 in Perry[15]. Knowing the percent glycerol the viscosity was easily obtained from the table on page 1742 of the Handbook of Chemistry and Physics[8] and the surface tension estimated from data on page 1720 of the same text.

The properties of air to be considered were density and viscosity. The density was calculated using the perfect gas law, while the viscosity was found from the alignment chart on page 31 of Perry[15].

CHAPTER V

DISCUSSION OF RESULTS

A total of 180 experimental runs were made. The results of these runs are presented in the form of curves and discussed in this chapter. The actual experimental values are contained in Tables 1 to 5 in the Appendix. A complete description of the packing and liquid properties is presented in Tables 6 and 7 in the Appendix.

I. PRESSURE DROP

The results of the pressure drop investigation are presented in Figures 3 to 7. The curves are plotted as ΔP vs G with parameters of constant L on log-log paper. Theoretically the volumetric gas rate would give a truer representation of flow conditions, but since the temperature and pressure changes were small, the result would be negligibly different from using the mass rate, and some tedious calculations were avoided.

The shape of the pressure drop curves is essentially the same for all three liquids, and does not differ markedly from those of other investigators who used different systems. In all cases the curve approximates a straight line in the middle portion, followed by a smooth

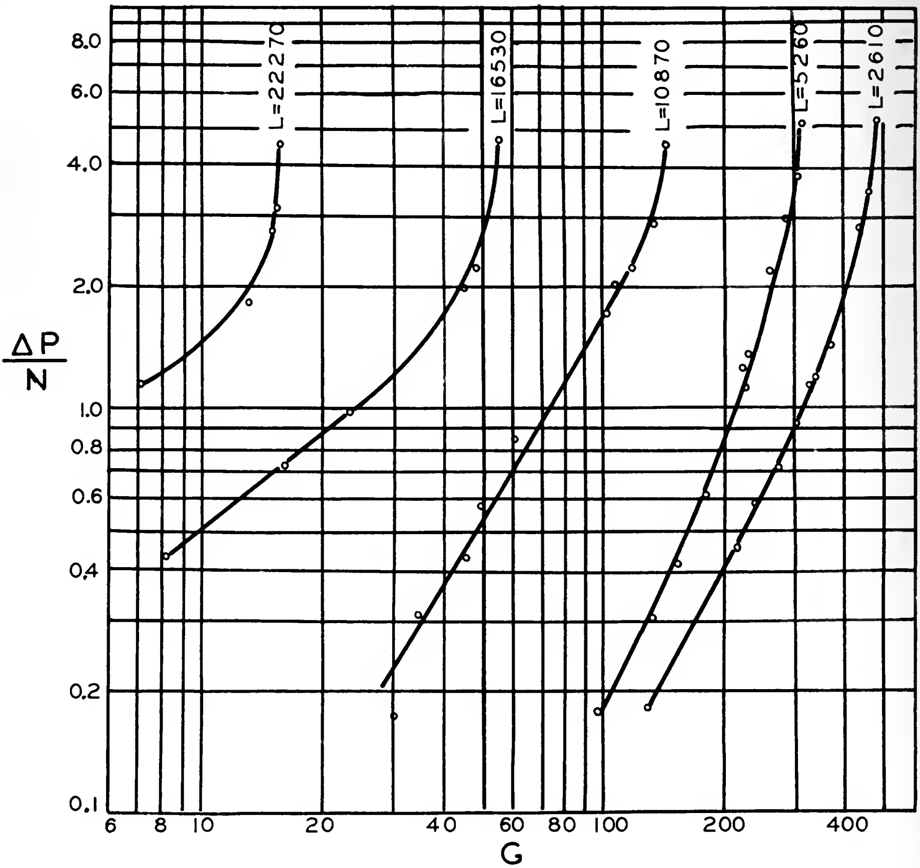


FIGURE 3

PRESSURE DROP DATA ON 3/8 INCH RASCHIG RINGS FOR WATER-AIR SYSTEM

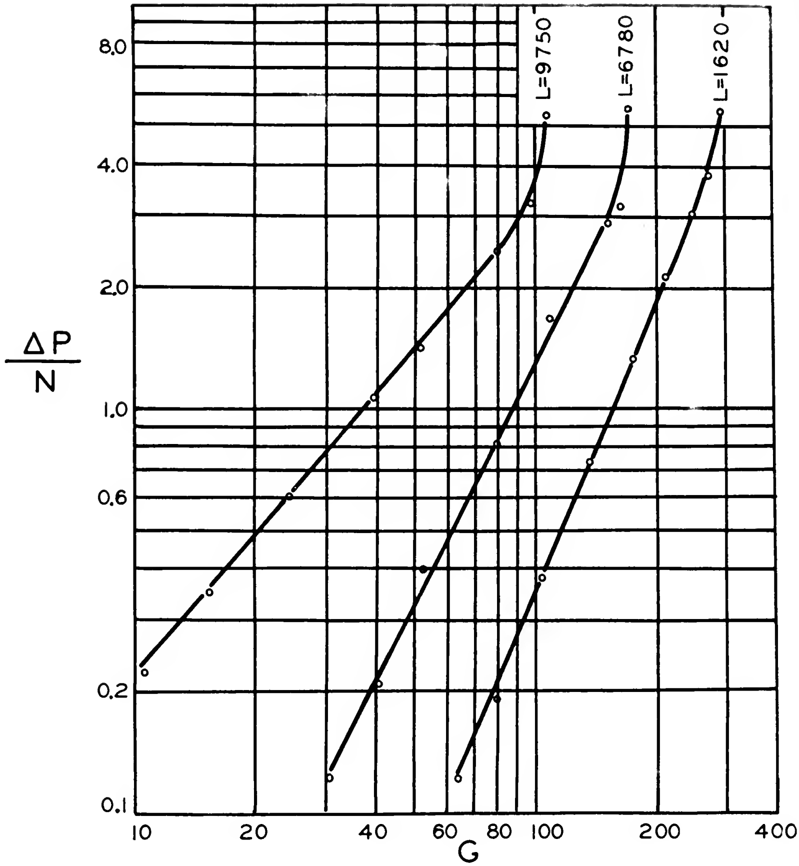


FIGURE 4

PRESSURE DROP DATA ON 3/8 INCH RASCHIG RINGS FOR 55.5% GLYCERINE-AIR SYSTEM

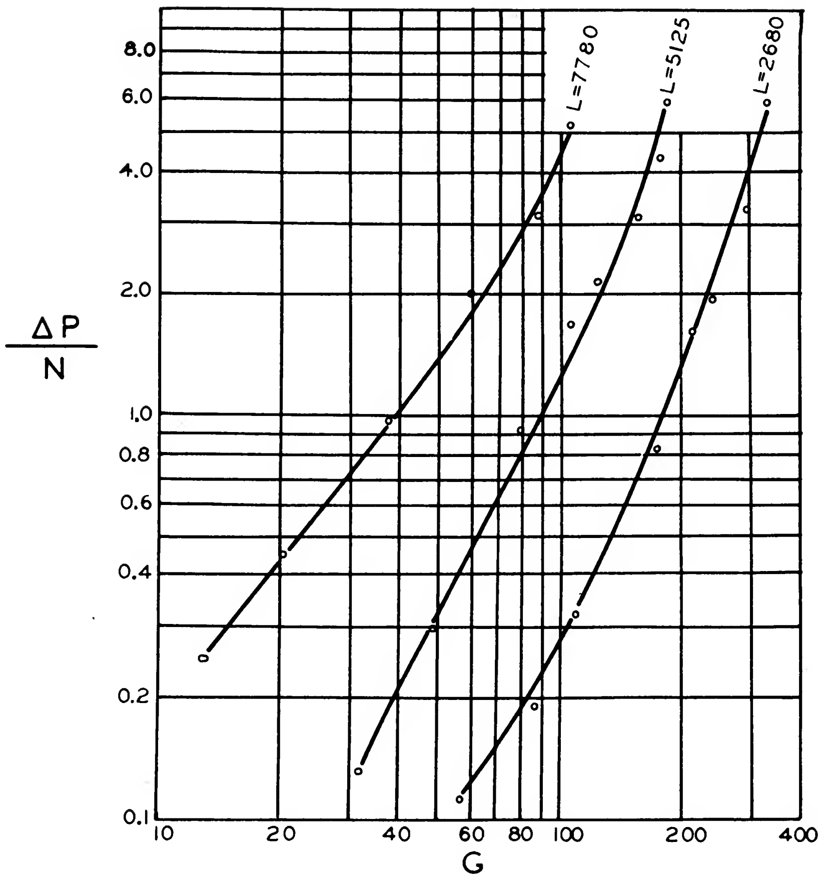


FIGURE 5

PRESSURE DROP DATA ON 3/8 INCH RASCHIG RINGS FOR 69.9% GLYCERINE-AIR SYSTEM

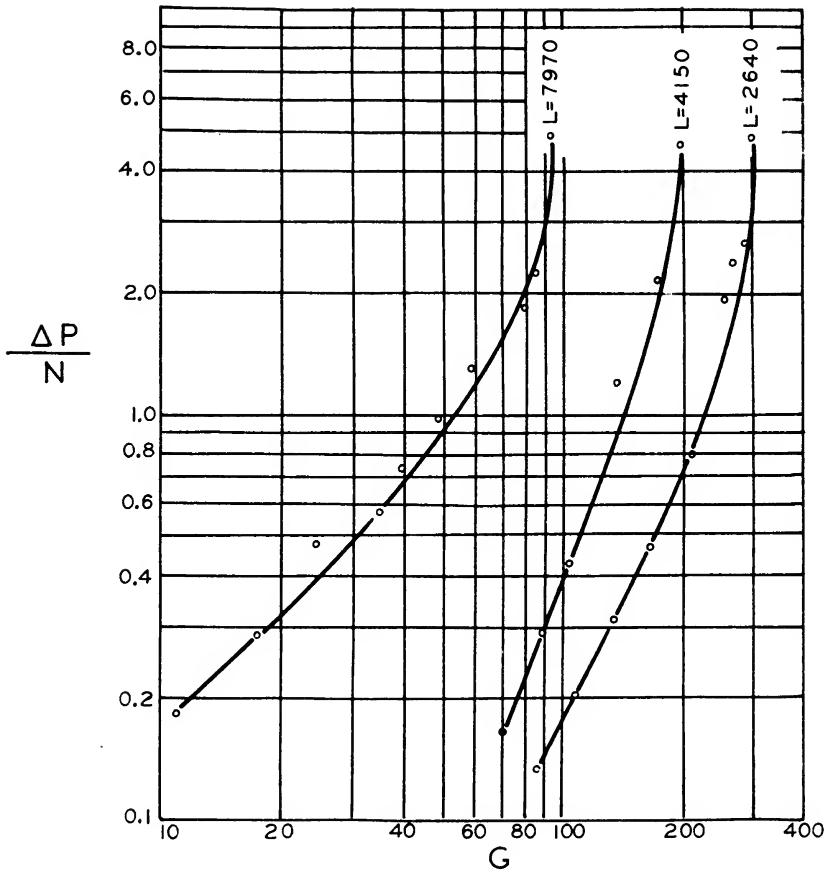


FIGURE 6

PRESSURE DROP DATA ON 3/8 INCH SPHERES FOR WATER-AIR SYSTEM

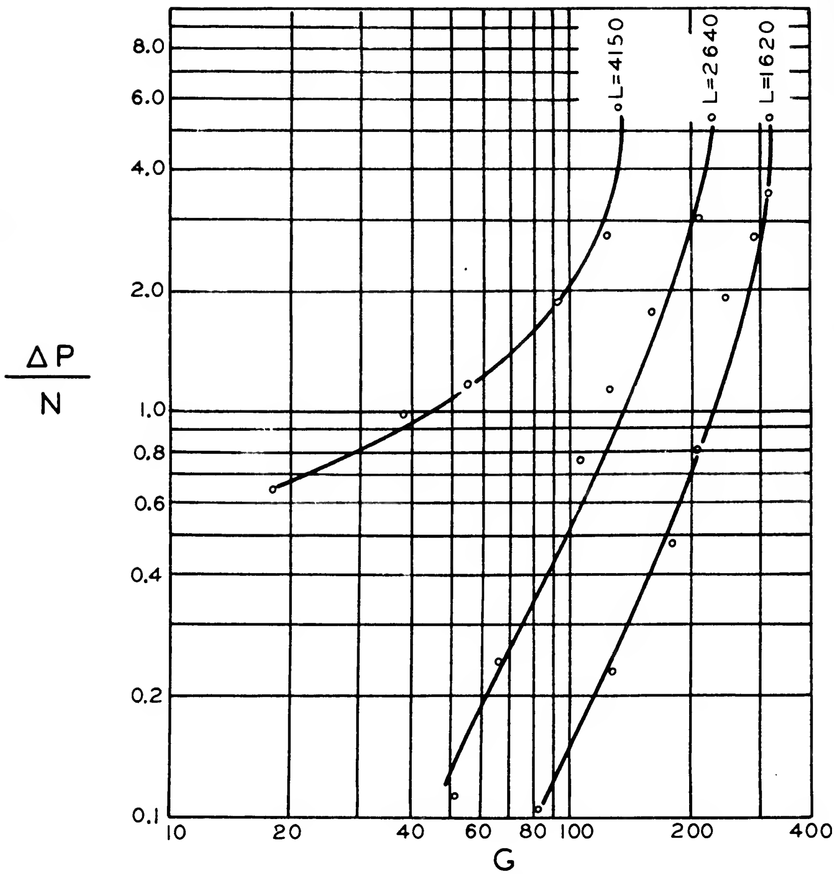


FIGURE 7

PRESSURE DROP DATA ON 3/8 INCH SPHERES FOR 55.5% GLYCERINE-AIR SYSTEM

transition to the vertical zone. The slope of this straight line portion is very near 2 at low liquid rates, but becomes progressively less as the liquid rate increases. The basis for the assumption that the curve may be considered 3 straight lines is evident in many of the curves. However a continually changing slope until the flooding point is reached is more truly representative of the experimental data, especially at the higher liquid rates.

Attempts to correlate the pressure drop with other variables was unsuccessful. The Brownell-Katz correlation[3] showed itself quite inadequate in the range of porosities covered by this work. And these porosities are representative of those found in counter-current packed towers.

The equation presented by Leva[11], $\Delta P = \propto \cdot 10^{\beta L} \frac{G^2}{\rho}$ may be expressed as $\Delta P = K \frac{G^2}{\rho}$ for a constant L. Thus, when ρ is constant, ΔP vs G is a parabola which has a slope of 2 on log-log paper. As pointed out above this is approximately correct at low liquid rates, but is not correct at high liquid rates.

The Zenz correlation[21] is similiar in that it is also limited by a "critical" liquid rate above which it does not apply. Another basic tenet of Zenz, upon which his correlation is based, is that the pressure drop at flooding is dependent only upon the type of packing and the

liquid properties and is independent of the gas and liquid rates at flooding. This was found to be no more than approximately true in some cases, and not so at all in others.

It was found most suitable to compare the effect of the various liquids by a comparison plot of ΔP vs G at a single liquid rate. Figure 8 is experimental data at L = 2640 for spheres. Figure 9 was drawn with data calculated from the equation $\Delta P = \alpha \cdot 10^{\beta L} \cdot \frac{G^2}{\rho}$. The constants α and β were determined from applicable experimental data of the Raschig rings. An inspection of these figures shows the great influence of both the liquid and the packing on the gas pressure loss. For example, with Raschig rings, at L = 3000 and G = 150, the ΔP is 0.25 inches of water per foot of packing height with water, 0.44 inches with 55.5% glycerine and 0.80 inches with 69.9% glycerine. In the case of spheres, at L = 2640, the pressure drop at G = 150 is 0.40 inches with water but is 1.50 inches with 55.5% glycerine, an increase of over 300%.

II. HOLDUP

The holdup measured simultaneously with the pressure drop is shown in figures 10 to 14 as a function of the gas rate at different liquid rates. An inspection of these

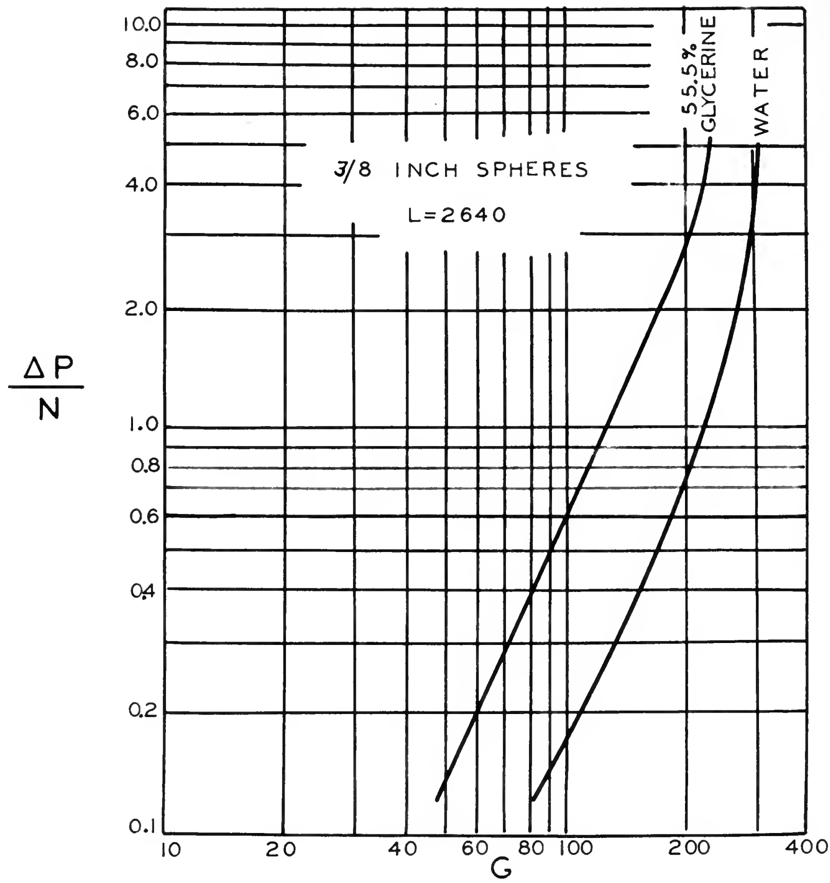


FIGURE 8

THE EFFECT OF LIQUID PROPERTIES ON PRESSURE DROP

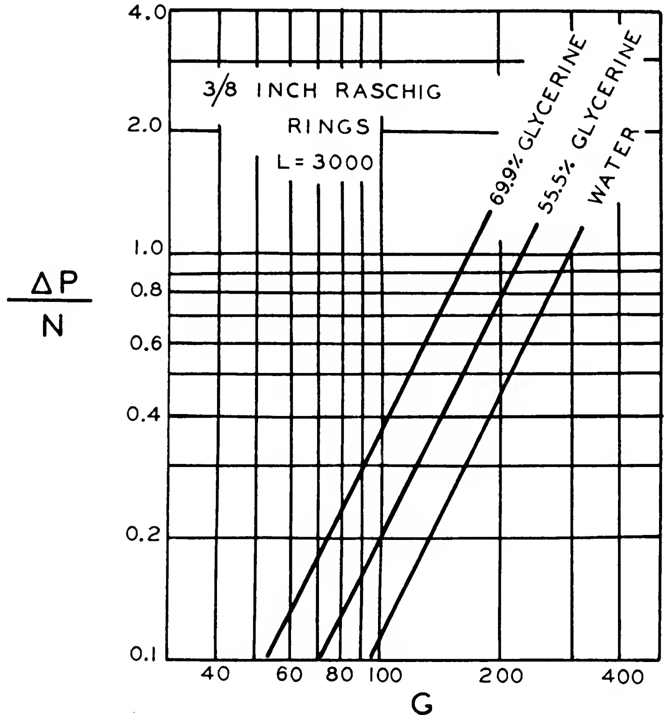


FIGURE 9
EFFECT OF LIQUID PROPERTIES
ON PRESSURE DROP

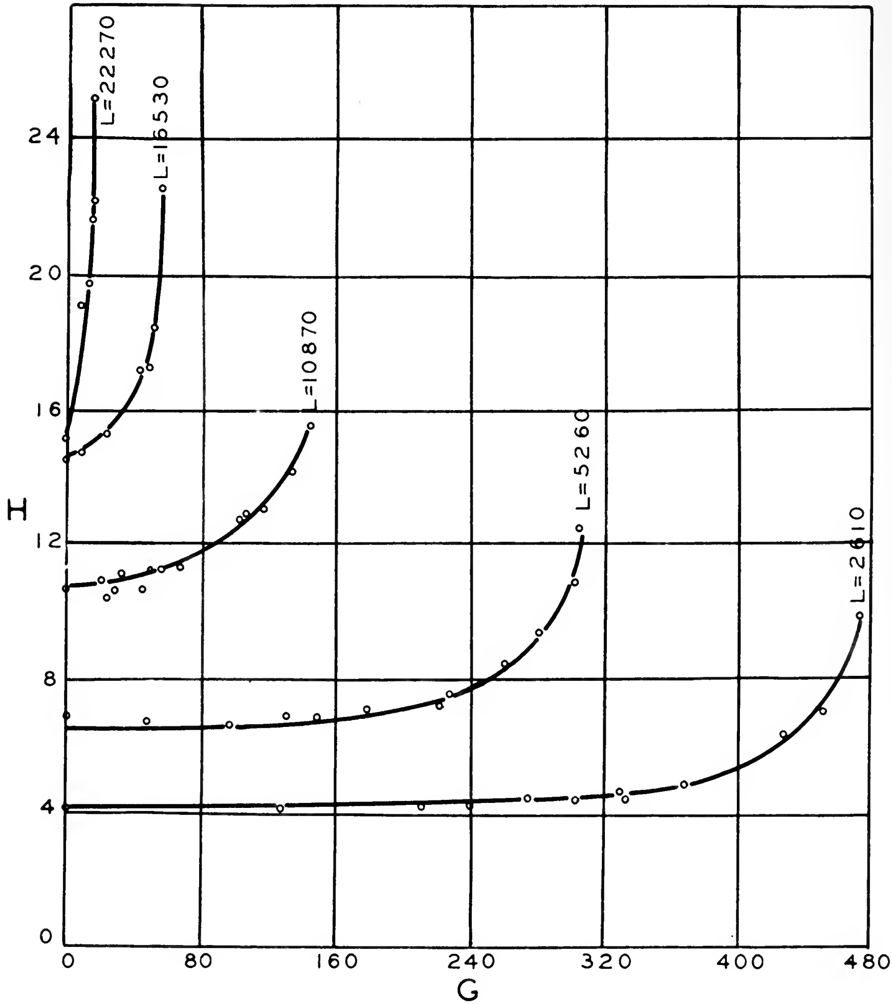


FIGURE 10

HOLDUP DATA ON 3/8 INCH RASCHIG RINGS FOR WATER-AIR SYSTEM

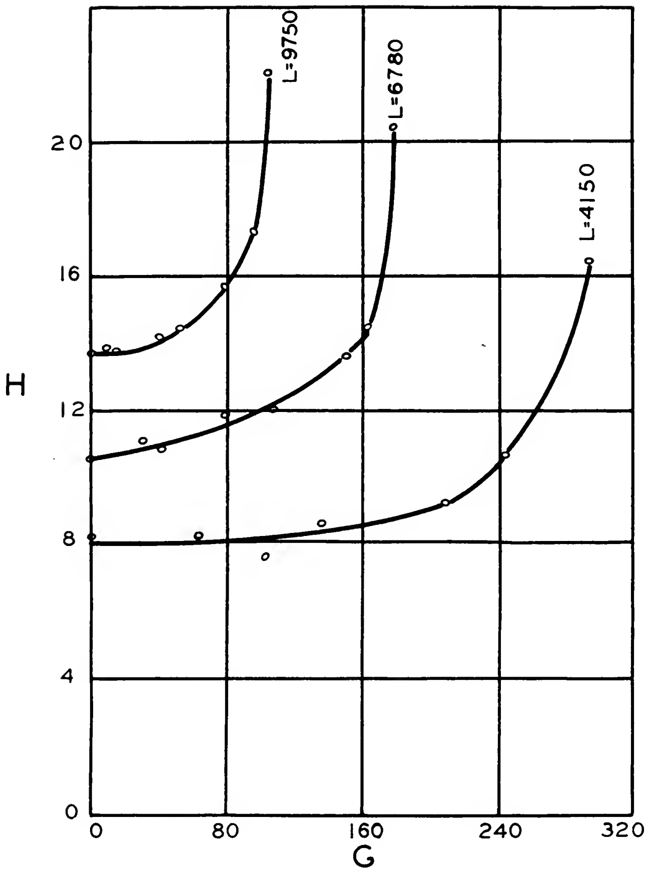


FIGURE II

HOLDUP DATA ON 3/8 INCH RASCHIG RINGS FOR 55.5% GLYCERINE-AIR SYSTEM

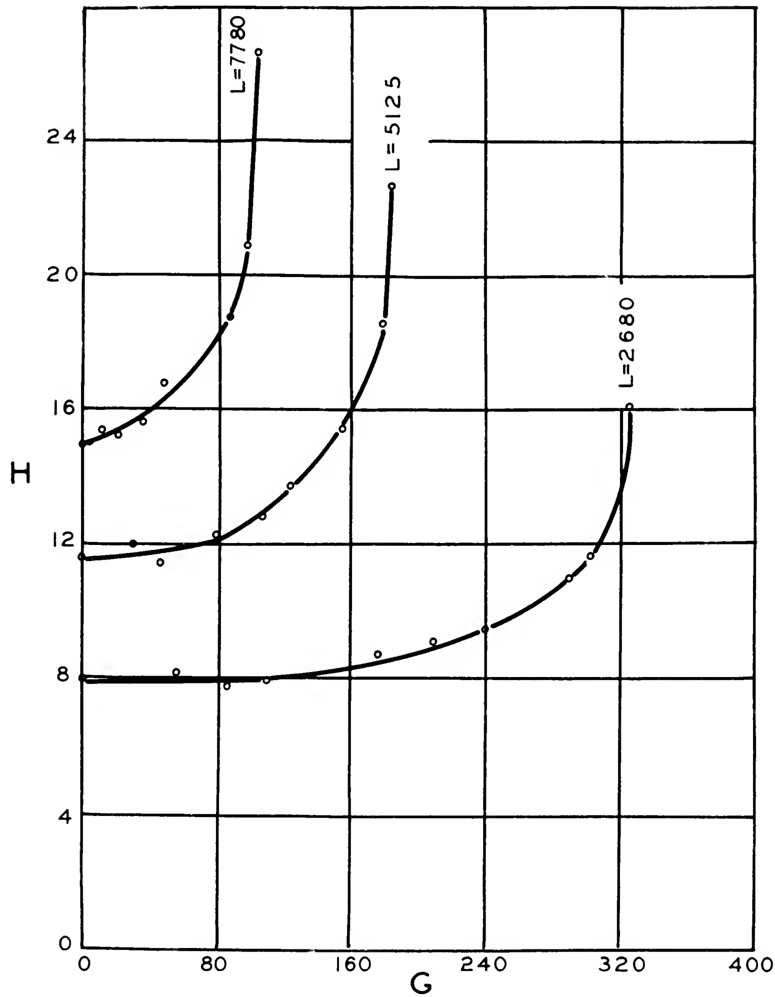


FIGURE 12

HOLDUP DATA ON 3/8 INCH RASCHIG RINGS FOR 69.9% GLYCERINE-AIR SYSTEM

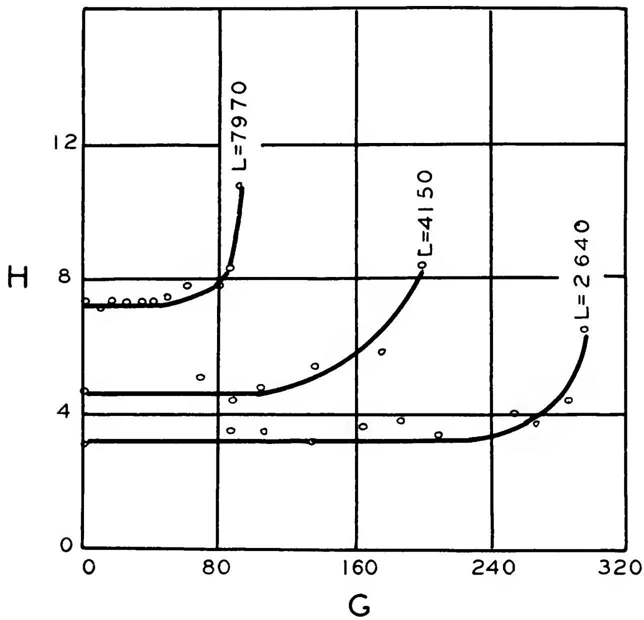


FIGURE 13
HOLDUP DATA ON 3/8 INCH SPHERES FOR WATER-AIR SYSTEM

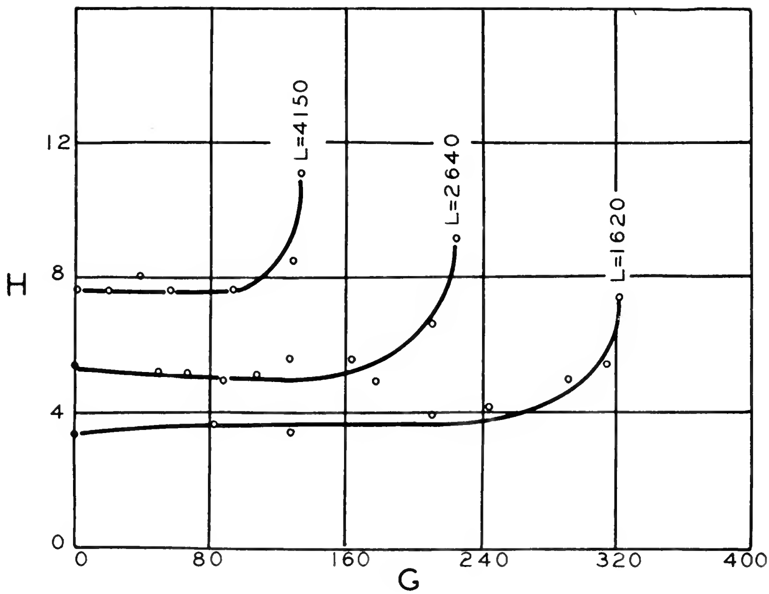


FIGURE 14

HOLDUP DATA ON 3/8 INCH SPHERES FOR 55.5% GLYCERINE-AIR SYSTEM

curves shows that the gas rate has no appreciable effect on holdup below the flooding region. However once the holdup begins to increase it does so quite sharply and is dependent on the gas rate in this region.

Since the holdup was found essentially independent of the gas rate in the usual operating range it was convenient to compare the holdup at zero gas flow for the various liquids and packings. The results of this comparison is shown in Figures 15 and 16.

In the case of Raschig rings it was found that the holdup is an exponential function of the liquid velocity and this exponent is essentially the same for all liquids. The spheres showed a similiar behaviour above L= 4000. Below this rate however the exponent was not constant. This latter feature was not found with Raschig rings down to L= 1500, although the exponent must of course eventually change to satisfy the condition that H=0 when L=0.

III. FLOODING VELOCITY

The method of correlating flooding velocity data proposed by Sherwood, et al,[18] and modified by Lobo, et al,[12] is reproduced as the solid line on Figure 17. The flooding velocities determined in the course of this work are also plotted on this figure.

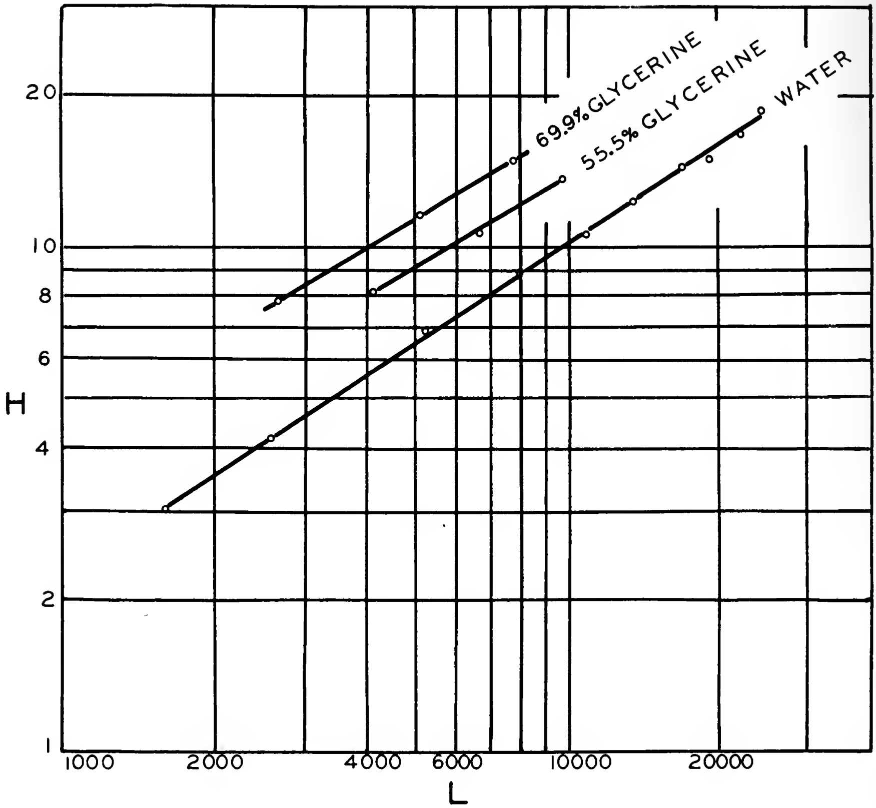


FIGURE 15

HOLDUP DATA ON 3/8 INCH RASCHIG RINGS FOR VARIOUS LIQUIDS AT ZERO GAS VELOCITY

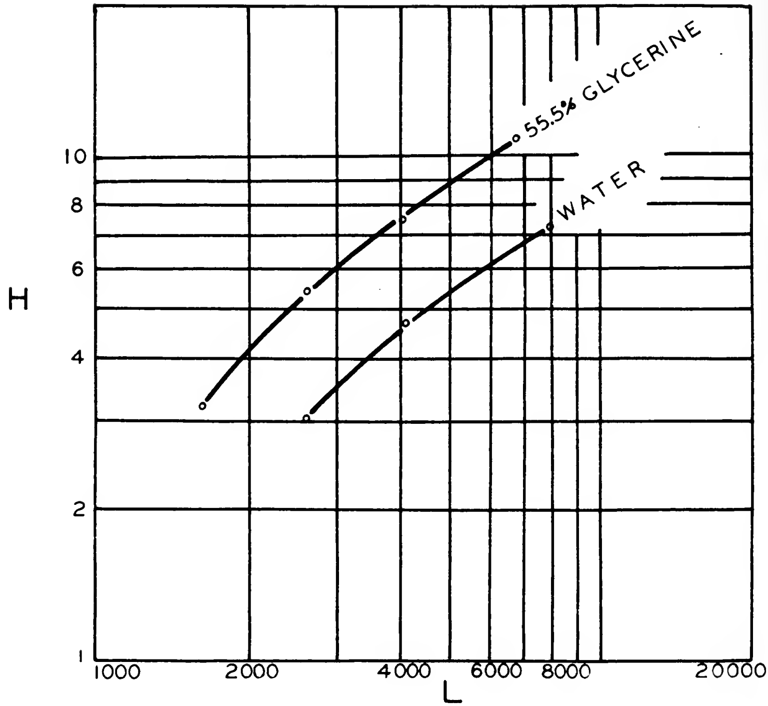


FIGURE 16

HOLDUP DATA FOR 3/8 INCH SPHERES FOR VARIOUS LIQUIDS AT ZERO GAS VELOCITY

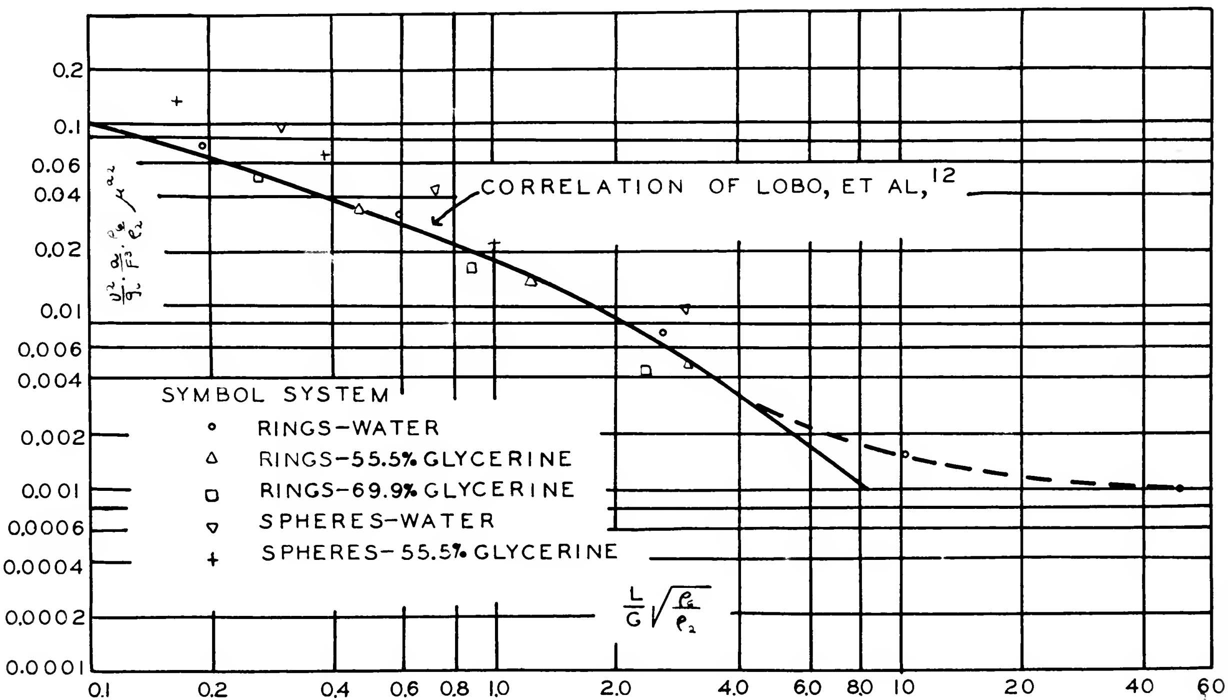


FIGURE 17

FLOODING VELOCITY CORRELATION

In as much as the most important use of this correlation is the determination of flooding velocities it was considered most advantageous to determine the average deviation of the flooding velocity calculated from this correlation with that found experimentally. The average deviation of 17 runs involving 3 liquids and 2 packing types was 15.3%. However the average deviation for rings, using 3 liquids was 6.20%, while for spheres, using 2 liquids it was 27.5%. Table 8, in the Appendix, contains data for the individual runs.

A further analysis of Figure 16 indicates the direction of extrapolation for the correlation. Although the original data of Lobo did not extend beyond $\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}} = 6$ he arbitrarily extended it to 8 as shown in the figure. This work indicates that the slope of the correlation curve is changing at a varying rate in this region and extrapolation into unexplored regions of very high liquid rates cannot be done with confidence.

CHAPTER VI

SUMMARY AND CONCLUSIONS

I. SUMMARY

Raschig rings and spheres were used in a 4 inch diameter glass column to obtain consistent data useful for understanding the effect of liquid properties on packed tower operation. With countercurrent flow of liquid and gas, pressure drop and holdup have been established for a series of liquid and gas flow rates. Water and glycerine solutions have been used to give liquids of varying density and viscosity. Air has been the gas phase throughout.

II. CONCLUSIONS

1. The equipment developed and standardized for this study is suitable for investigating packed tower operation.

2. Various packings and liquids have log ΔP vs. log G curves of the same shape, however this shape has not been rigidly established. In many cases it may be represented by 3 straight lines with two break points. However a smooth curve appears to be more truly representative of experimental data.

3. Holdup is essentially independent of gas velocity below the flooding region. However it increases markedly in this region. This is true regardless of the packing type and liquid properties.

4. Holdup varies exponentially with liquid rate both with and without gas flowing as long as the flooding region is not entered.

5. The correlation of Sherwood, et al[18] as modified by Lobo, et al[12] is satisfactory for calculating flooding velocities using Raschig rings with liquids of various properties. It is less satisfactory when spheres are the packing material.

6. More data is necessary at high liquid rates before the correlation mentioned in 5 can be extrapolated with confidence.

BIBLIOGRAPHY

1. Bain, W. A., and O. A. Hougen, "Flooding Velocities in Packed Columns," Trans. Am. Inst. Chem. Engrs., 40:29-49, 1944.

2. Brownell, L. E., and D. L. Katz, "Flow of Fluids Through Porous Media-Part I," Chem. Eng. Prog., 43:537-548, 1947.

3. __________, "Flow of Fluids Through Porous Media-Part II," Chem. Eng. Prog., 43:601-612, 1947.

4. Brownell, L. E., H. S. Dombrowski, and C. A. Dickey, "Flow of Fluids Through Porous Media-Part IV," Chem. Eng. Prog., 46:415-423, 1950.

5. Chilton, T. H., and A. P. Colburn, "Pressure Drop in Packed Tubes," Ind. Eng. Chem., 23:913-931, 1931.

6. Cooper, C. M., R. J. Christl, and L. C. Perry, "Packed Tower Performance at High Liquor Rates," Trans. Am. Inst. Chem. Engrs., 37:979-996, 1941.

7. Elgin, J. C., and F. B. Weiss, "Liquid Holdup and Flooding in Packed Towers," Ind. Eng. Chem., 31:435-445, 1939.

8. Hodgman, Charles D., Editor, Handbook of Chemistry and Physics, Cleveland, Ohio: Chemical Rubber Publishing Co., 1946. 2686pp.

9. Jesser, B. W., and J. C. Elgin, "Studies of Liquid Holdup in Packed Towers," Trans. Am. Inst. Chem. Engrs., 39:277-298, 1943.

10. Leva, Max, "Pressure Drop Through Packed Tubes-Part I," Chem. Eng. Prog., 43:549-555, 1947.

11. Leva, Max, Tower Packings and Packed Tower Design. Akron, Ohio: The United States Stoneware Co., 1951. 119pp.

12. Lobo, W. E., Leo Friend, F. Hashmall, and F. Zenz, "Limiting Capacity of Dumped Tower Packings," Trans. Am. Inst. Chem. Engrs., 41:693-710, 1945.

13. Moody, L. F., "Friction Factors for Pipe Flow," Trans. Am. Soc. Mech. Engrs., 66:671-682, 1944.

14. Payne, J. W., and B. F. Dodge, "Rate of Absorption of Carbon Dioxide in Water and in Alkaline Media," Ind. Eng. Chem., 24:630-637, 1932.

15. Perry, J. H., Editor, Chemical Engineers' Handbook. New York: McGraw-Hill, 1950. 1942pp.

16. Simmons, C. W., and H. B. Osborn, "Tower Absorption Coefficients," Ind. Eng. Chem., 26:592-531, 1934.

17. Sherwood, Thomas K., Absorption and Extraction. New York: McGraw-Hill, 1937. 278pp.

18. Sherwood, T. K., G. H. Shipley and F. A. L. Holloway, "Flooding Velocities in Packed Columns," Ind. Eng. Chem., 30:765-769, 1938.

19. White, A. McL., "Pressure Drop and Loading Velocities in Packed Towers," Trans. Am. Inst. Chem. Engrs., 31:390-408, 1935.

20. Zeisberg, Fred C., "Resistance of Absorption Tower Packing to Gas Flow," Chemical and Metallurgical Engineering, 21:765-766, 1919.

21. Zenz, Frederik A., "Mechanism of Countercurrent Gas-Liquid Flow Through Packed Towers," Chem. Eng. Prog., 43: 415-429, 1947.

APPENDIX

TABLE 1

DATA ON 3/8 INCH RASCHIG RINGS FOR WATER-AIR SYSTEM

L	Run No.	G	P/N	H
2,610	2	0.0	0.00	4.2
	48	129.4	0.18	4.2
	45	214.0	0.45	4.2
	46	242.4	0.58	4.2
	47	275.8	0.72	4.4
	49	304.3	0.93	4.4
	50	330.0	1.15	4.6
	51	335.2	1.19	4.4
	65	370.2	1.45	4.9
	62	431	2.88	6.3
	63	453	3.45	7.1
	64	474	5.26	9.9
5,260	3	0.0	0.00	6.8
	12	96.9	0.18	6.6
	25	131.4	0.30	6.8
	24	151.0	0.41	6.8
	13	152.0	0.41	6.8
	15	180.3	0.61	7.1
	18	224.2	1.26	7.1
	17	226.8	1.15	7.1
	14	229.3	1.37	7.6
	21	260.2	2.20	8.5
	22	284.0	2.97	9.4
	19	304.0	3.78	10.9
	19A	309.3	5.17	-
10,870	5	0.00	0.00	10.6
	54	30.20	0.17	10.6
	41	34.04	0.31	11.1
	43	45.4	0.42	10.6
	33	49.0	0.57	11.3
	40	59.3	0.84	11.3
	42	101.7	1.70	12.6
	27A	105.2	2.01	12.8
	28	118.2	2.24	13.0
	29	134.1	2.87	14.2
	30	143.3	4.47	15.7

TABLE 1 (continued)

DATA ON 3/8 INCH RASCHIG RINGS FOR WATER-AIR SYSTEM

L	Run No.	G	P/N	H
16,530	7	0.00	0.00	14.47
	52	8.10	0.43	14.70
	53	15.99	0.72	15.65
	35	23.20	0.97	15.17
	36	45.8	2.00	17.07
	37	48.5	2.23	17.07
	38	53.2	2.97	18.30
	39	55.2	4.57	22.35
22,270	8	0.00	0.00	15.18
	60	7.07	1.13	18.98
	56	12.90	1.83	19.68
	57	14.96	2.78	21.60
	58	15.31	3.17	22.13
	59	15.48	4.58	25.32

TABLE 2

DATA ON 3/8 INCH RASCHIG RINGS FOR 55.5% GLYCERINE-AIR SYSTEM

L	Run No.	G	P/N	H
1,620	124	0.0	0.00	5.4
4,150	108	0.0	0.00	8.2
	110	63.4	.11	8.2
	111	78.8	.19	8.2
	109	101.7	.38	7.5
	112	136.1	.74	8.6
	113	175.2	1.33	-
	114	210.4	2.13	9.2
	115	244.0	3.00	10.6
	116	270.6	3.81	-
	117	287.0	5.5	16.4
6,780	107	0.0	0.00	10.6
	118	30.4	.12	11.1
	119	40.0	.21	10.8
	100	51.6	.40	-
	95	78.8	.82	11.8
	96	106.8	1.68	11.8
	97	150.6	2.85	13.5
	98	163.0	3.33	14.4
	99	179.3	5.50	20.4
9,750	106	0.0	0.00	13.7
	123	10.2	.24	13.7
	122	15.5	.45	13.7
	121	24.3	.60	14.9
	120	38.9	1.05	14.2
	101	51.6	1.40	14.4
	102	79.4	2.42	15.6
	104	96.9	3.47	17.3
	103	105.2	5.27	22.1

TABLE 3

DATA ON 3/8 INCH RASCHIG RINGS FOR 69.9% GLYCERINE-AIR SYSTEM

L	Run No.	G	P/N	H
2,680	76	0.0	0.00	7.9
	75	56.2	0.11	8.2
	71	87.6	0.19	7.7
	72	111.3	0.32	7.9
	73	131.4	0.43	7.7
	70	176.8	0.83	8.7
	74	211.4	1.66	9.1
	69	240.5	1.98	9.4
	68	291.4	3.32	11.0
	66	324.0	6.07	18.2
5,125	84	0.0	0.00	11.5
	91	32.0	0.13	12.0
	77	48.4	0.30	11.3
	78	79.9	0.93	12.2
	79	107.2	1.69	12.7
	80	124.8	2.17	13.7
	81	154.8	3.18	15.4
	82	179.0	4.43	18.5
	83	184.0	6.02	22.7
7,780	85	0.00	0.00	14.9
	93	12.89	0.25	15.32
	90	20.60	0.45	15.1
	92	37.60	0.97	15.69
	89	58.7	2.02	16.8
	86	88.7	3.09	18.79
	87	99.0	4.00	20.8
	88	105.8	5.28	26.6

TABLE 4

DATA ON 3/8 INCH SPHERES FOR WATER-AIR SYSTEM

L	Run No.	G	P/N	H
2,640	162	0.0	0.00	3.0
	159	85.5	.13	3.5
	160	106.8	.20	3.5
	161	134.0	.32	3.2
	163	165.0	.47	3.7
	164	210.5	.80	3.5
	165	253.0	1.95	4.2
	166	267.0	2.39	3.9
	167	288.5	2.66	4.4
	168	296.3	4.85	6.6
4,150	180	0.0	0.00	4.7
	158	70.1	.16	5.2
	156	88.2	.27	4.4
	157	102.6	.42	4.9
	155	135.5	1.20	5.4
	154	175.2	2.13	5.9
	153	198.0	4.73	8.5
7,970	179	0.00	0.00	7.3
	178	10.82	.18	7.1
	177	17.21	.28	7.3
	176	24.65	.47	7.3
	175	34.6	.57	7.3
	174	39.8	.72	7.3
	173	49.5	.97	7.5
	172	59.8	1.30	7.8
	169	79.9	1.82	7.8
	170	86.2	2.23	8.3
	171	92.8	4.87	10.8

TABLE 5

DATA ON 3/8 INCH SPHERES FOR 55.5% GLYCERINE-AIR SYSTEM

L	Run No.	G	P/N	H
1,620	152	0.0	0.00	3.2
	136	81.9	.10	3.7
	135	127.2	.23	3.5
	133	177.8	.48	3.9
	134	210.4	.81	3.9
	132	244.5	1.96	4.2
	129	291.0	2.77	4.9
	130	313.5	3.51	5.4
	131	319.5	5.40	7.5
2,640	151	0.0	0.00	5.4
	145	48.9	.10	5.2
	144	51.6	.11	5.4
	142	65.4	.24	5.1
	137	86.0	.29	4.9
	143	107.2	.76	5.1
	139	125.8	1.15	5.6
	138	162.9	1.80	5.6
	140	211.2	2.98	6.6
	141	225.0	5.28	9.2
4,150	150	0.0	0.00	7.5
	147	18.0	.65	7.5
	146	38.2	1.00	8.0
	127	55.6	1.18	7.6
	126	93.7	1.87	7.7
	125	127.2	2.75	8.5
	128	133.0	5.38	11.1
6,780	148	0.0	0.00	10.9
9,750	149	0.0	0.00	12.8

TABLE 6

PACKING CHARACTERISTICS

	Raschig Rings	Spheres
Nominal Size, inches	3/8	3/8
No. units/ cu. ft. of tower	27,700	32,700
Packing surface, sq.ft./cu. ft. of tower	182.0	111.2
Dry Void Space, cu.ft./ cu.ft. of tower	0.668	0.388
Drained Void Space, cu.ft./cu.ft. of tower		
Water	0.650	0.377
55.5% Glycerine	0.642	0.387
69.9% Glycerine	0.637	———

TABLE 7

LIQUID PROPERTIES

	Water	55.5% Glycerine	69.9% Glycerine
Density, lbs./cu. ft.	62.4	71.1	73.4
Viscosity, centipoises	1.39	6.38	15.0
Surface Tension, dynes/cm.	74.5	69	67

TABLE 8

FLOODING POINT DATA

System	Run No.	$\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$	$\frac{u^2}{g_c} \frac{a}{F^3} \cdot \frac{\rho_G}{\rho_L} \cdot \mu^{0.2}$ Actual	Correl.	Dev. of u
Rings-Water	64	0.1907	0.0776	0.068	0.0652
	19A	0.592	0.0330	0.029	0.0705
	30	2.62	0.00713	0.0063	0.0643
	39	10.40	0.00152	-	-
	59	49.8	0.000827	-	-
Rings-55.5% Gly.	117	0.470	0.0338	0.035	0.0160
	99	1.229	0.01325	0.015	0.0572
	103	3.013	0.00456	0.0052	0.0638
Rings-69.9% Gly.	66	0.265	0.0493	0.054	0.0432
	83	0.893	0.01593	0.0203	0.1158
	88	2.360	0.00528	0.0072	0.1470
Spheres-Water	168	0.304	0.0947	0.049	0.388
	153	0.729	0.0422	0.028	0.234
	171	2.97	0.0093	0.0053	0.321
Spheres-55.5% Gly.	131	0.1648	0.1310	0.075	0.321
	141	0.382	0.0651	0.041	0.268
	128	1.020	0.0226	0.018	0.120

VITA

William James Walsh was born in St. Louis, Mo. on November 29, 1920 the son of William J. and Laura S. Walsh. He attended Xavier High School and Columbia University in New York City and was granted the degree of Bachelor of Science from the latter institution in October, 1943.

He entered the Navy immediately upon graduation and was commissioned Ensign, USNR in February, 1944. For the remainder of the war and until October 1946 he was Engineer Officer of the U.S.S. McDermut, DD677.

Upon leaving the Navy he was employed by the General Electric Company as a chemical engineer at the Hanford Engineer Works, Richland, Washington. In February, 1947 he accepted a commission in the regular Navy and was assigned to the Long Beach Naval Shipyard where he served as Ship Superintendent and later Assistant Shop Superintendent.

In June 1949 he was transferred to the U. S. Naval Postgraduate School for advanced training in engineering. After one year he was sent to Lehigh University for further work in chemical engineering. Lehigh granted him the degree of Master of Science in October 1951. He continued his research during the year 1951-1952 working for the degree of

Doctor of Philosophy with special work in the field of chemical engineering, for which this dissertation is a partial requirement.

Date Due

Thesis
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Walsh

An experimental study of the effect of li uid properties on packed tower operation.